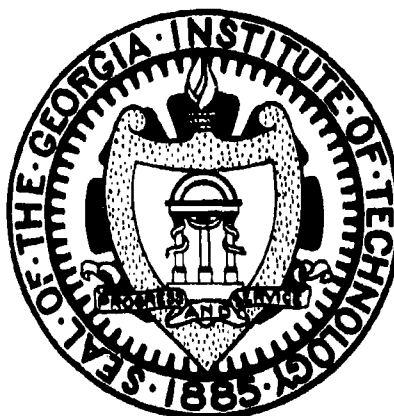


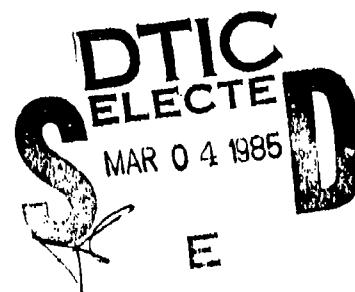
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BEHAVIOR OF ADVANCED AND COMPOSITE STRUCTURES

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Final Scientific Report  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  <b>This final report summarizes the objectives and accomplishments of three tasks performed under a one year grant from AFOSR to complete ongoing research. Task 1 is concerned with the development and validation of new bending and buckling theories for composite structures. Task 2 is the experimental investigation of the effects of delamination on the compressive buckling and postbuckling of composite laminated panels. Task 3 is an experimental evaluation of damage tolerance of composite isogrid panels. Isogrid is a stiffening concept</b>		

## 20. Abstract (cont'd.)

that employs a repetitive equilateral triangular pattern of ribs. Papers, reports, and presentations resulting from this research are listed. In Task 1, new theories which include the effects of transverse shear strain, transverse normal strain, stretching related warping and bending related warping on composite laminates, orthogonally stiffened composite plates and composite isogrid plates have been developed, validated and applied. In the case of isogrid panels, comparisons of predictions for compressive buckling have been made with experiment and found to be quite good.

In Task 2, the structural consequences of delamination on compressive postbuckling of composite panels. The panels are of quasi-isotropic, symmetric ply-layup, graphite/epoxy with single delaminated zones between the central plies, all delaminations of the same size (ten percent of the panel area) but of different rectangular shapes. Initial postbuckled stiffness, ultimate failure loads and failure modes for the panels were determined. The data indicate that delaminations reduce the initial postbuckled stiffness. They do not influence, however, the failure process. This is because they were placed in the center of the panels and ultimate failure began at the corners. *Operator cancelled key...*

In Task 3, experimental results confirm the high degree of damage tolerance achieved by composite isogrid structure. This work, which was begun last year, has been completed. In addition, analytical work aimed at correlating earlier isogrid experimental data with theory has been completed and was cited earlier under Task 1.

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## INTRODUCTION

The work described herein was performed at the School of Aerospace Engineering, Georgia Institute of Technology during the period 1 January 1982 - 31 January 1983. Professor Lawrence W. Rehfield was the Principal Investigator. The research is divided into three tasks. Task 1 is "Theory and Analysis of Advanced Structures". It is concerned with the continued development and application of new theories of structural behavior which include effects that are especially important to composite structures.

Task 2, "Failure Processes in Compression for Composites", focuses on the structural consequences of delamination in composite laminates. Task 3 addresses experimental methodology and theory for the evaluation of advanced structural concepts. Particular emphasis has been placed upon the study of damage tolerance in continuous filament composite structures.

For convenience, this report contains a separate section devoted to each task.

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## TASK 1: THEORY AND ANALYSIS OF ADVANCED STRUCTURES

### Objectives

The objectives of this research task were: (1) to continue to develop new theories of structural behavior with improved predictive capability, (2) to validate the theories in systematic ways, and (3) to apply them to generic problems for which new insight is needed. The direction of the work is oriented toward structures constructed of modern composite materials. Classical theories ignore three effects which are significant for certain geometries and stiffness characteristics - transverse shear strain, transverse normal strain and section warping. The new theories include these effects in an appropriate manner which still retains the simplicity of an engineering approach.

### Accomplishments

Some work completed under a previous grant, AFOSR-81-0056, has been reported and published since the current grant was initiated. It is included as effort was devoted to bringing it to completion. It is marked by an asterisk. In general, work on this task has been given a major emphasis and it has progressed very well. The predictive capability of the equations developed is exceptional and often strikingly precise. An extended range of structural modeling is achieved with a negligible increase in complexity over conventional transverse shear deformation theories.

The following accomplishments were achieved:

- (1) A paper<sup>1</sup> on our new planar bending theory has appeared in the AIAA Journal.\*
- (2) An extensive study<sup>2</sup> of planar bending including statics, dynamics, buckling and numerous applications has been completed.\*

- (3) A theory for bending and buckling of orthogonally stiffened woven grid composite plates has been completed.<sup>3</sup> The results were reported at the 24th Israel Annual Conference on Aviation and Astronautics and will be published in the Israel Journal of Technology.
- (4) A theory for isogrid stiffened composite structures that is similar to the above has been developed and utilized to provide predictions for comparison with earlier experiments.<sup>4,5</sup> The correlation is good. These findings appear in the Proceedings of the 4th International Conference on Composite Materials.
- (5) A planar bending theory for composite laminates has been completed and validated by comparison of predictions with available exact solutions. The agreement is exceptional. This work was presented at the Symposium on Advances and Trends in Structural and Solid Mechanics and appears in the Journal of Computers and Structures.<sup>6</sup>
- (6) A fully three-dimensional beam bending theory has been developed and evaluated. It appears in R. R. Valisetty's Ph.D. Thesis.<sup>7</sup>
- (7) The planar bending theory, item (5), has been extended to the general case of composite laminates and validated by comparison with available exact solutions. The results will be presented at the upcoming AIAA SDM Conference at Lake Tahoe.<sup>8</sup>
- (8) The work on analysis of composite laminates has yielded a method of analyzing interlaminar stresses which we believe is quite promising. Early results appear in Ref. 7. An abstract has been submitted for a paper to be presented at the ASTM Symposium on Delamination and Debonding of Materials.<sup>9</sup>
- (9) Our theoretical work has been put to practical use in the study of the influence of hygrothermal conditioning on compressive buckling of

composite structures. Our results clarify the mechanisms and the importance of these effects in buckling critical airframe structure. They will be presented at the upcoming AHS National Specialists' Meeting on Composite Structures.<sup>10</sup>

Major emphasis has been given to this task. The work has a unique character. It is believed it will impact directly modeling technology for composite structures in the future.

## TASK 2: FAILURE PROCESSES IN COMPRESSION FOR COMPOSITES

### Objective

Compressive failure processes are poorly understood for composites. More efficient utilization of these materials requires the acquisition of both understanding and predictive capability. The objective of this task is to determine the structural consequences of delamination. Laminated composite panels with prescribed areas of delamination have been manufactured by Lockheed Georgia Company. These were subjected to nondestructive buckling and vibration tests and finally tested to failure in a postbuckled state.

### Accomplishments

The panel specimens have been designed with a quasi-isotropic symmetric ply layup with a single delaminated zone between the central plies. The delaminated area is ten percent of the panel area, which is thought to be an upper limit to the size encountered in service between inspections. The total area of delamination has been held fixed, but different rectangular shaped delamination zones have been manufactured into the panels. This permits the influence of shape of the delaminated zone to be studied in a systematic way.

The results obtained indicate that delaminations of the size and type considered do not produce drastic changes in stiffness-related behavior. This supports the widely-held belief that resin matrix composites are damage tolerant. Findings have been presented at an ASTM Conference.<sup>11</sup>

After the stiffness-related buckling and vibration experiments were completed, the panels remained intact for further experiments. An investigation of the effect of the prescribed delaminations on compressive postbuckling behavior was undertaken. Initial postbuckled stiffness, ultimate failure loads and failure modes for the panels were determined. The data indicate that delaminations reduce the initial postbuckled stiffness. The delaminations, however, in spite of



their large size, do not significantly influence the failure process. This is due to the fact that the failure sites were similar in all cases and situated away from the delaminated zones. The results were presented at the 6th DOD/NASA Composite Structures Design Conference.<sup>12</sup>

#### Analysis of Compression Testing

In addition to the above work on delamination, an analytical investigation into the sensitivity of compression test specimens to boundary restraint and departures from ideal test conditions was initiated. This was motivated by experiences encountered during the experimental phase of the earlier work on panels. The investigation will be completed under another grant concerned with fracture processes. An abstract has been written and a paper accepted for presentation at the upcoming 2nd U.S.-Japan Conference on Composites sponsored by the ASTM.<sup>13</sup>

### TASK 3: EXPERIMENTAL EVALUATION OF ADVANCED STRUCTURAL CONCEPTS

#### Objective

This task was intended to develop test methods appropriate to the element level of scale and complexity for advanced structural concepts. The focus has been upon damage tolerance of continuous filament composite stiffened structures. A complete testing methodology has been developed and implemented which serves as a model for this type of study.

#### Accomplishments

The search for efficient, light-weight aerospace structural concepts is a continuing process. One promising concept is isogrid. It is a stiffening concept that employs a repetitive equilateral triangular pattern of ribs. The name "isogrid" is derived from the fact that the triangular grid exhibits isotropic properties in a gross or overall sense.

Previously obtained experimental results have demonstrated that continuous filament composite isogrid is very tolerant of damage in stiffness controlled applications. These experiments have provided data on load path redistribution due to damage, as well as overall natural frequency and buckling load data. For maximum benefit to be derived from the accumulated data, correlation with a finite element simulation of the damaged structure is needed. Our investigation of damage tolerance of isogrid structure has been completed with the completion of testing and finite element analysis of behavior. The results demonstrate not only the high degree of damage tolerance, but also the fact that the behavior of damaged structures can be analytically predicted.

The complete results have been presented at an ASTM symposium and will appear in the proceedings.<sup>14</sup>

Additional analytical work aimed at correlating earlier isogrid experimental data with theory was cited earlier under Task I and appears in Refs. 4 and 5.

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